

# The 126 GeV Discovery: Implications for the SM and MSSM

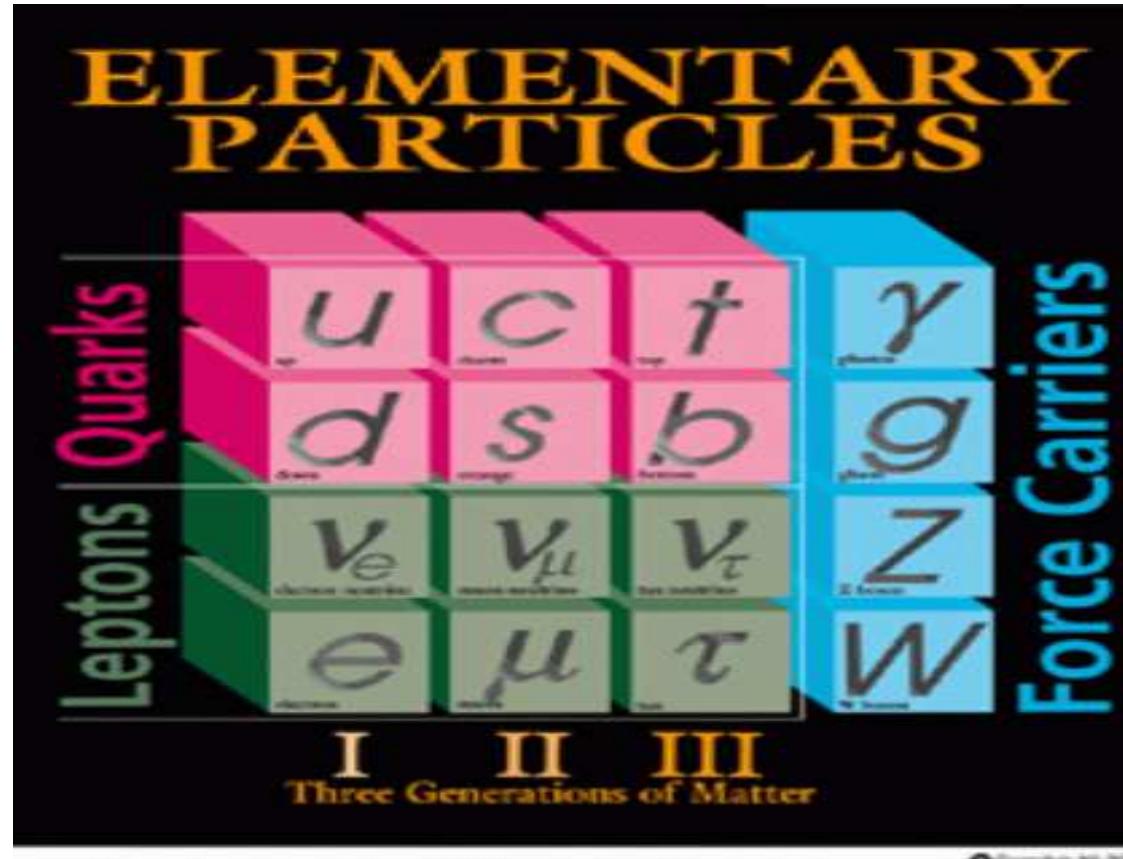
*Sven Heinemeyer, IFCA (CSIC, Santander)*

BNL, 10/2012

1. Introduction
2. Implications for the SM
3. Towards a coupling determination
4. Implications for the MSSM
5. Conclusions

## 1. Introduction

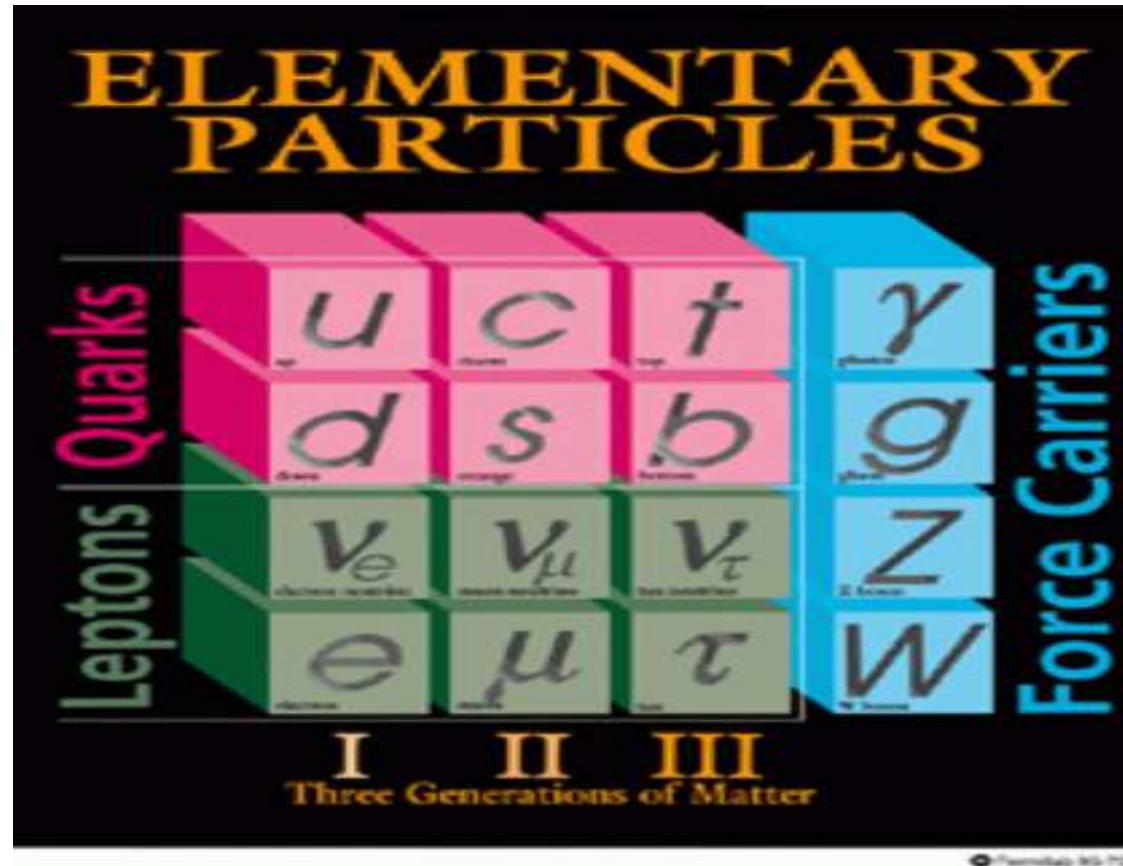
Current status of knowledge: the Standard Model (SM)



→ all particles experimentally seen

## 1. Introduction

Current status of knowledge: the Standard Model (SM)



→ all particles experimentally seen

→ but it predicts massless gauge bosons . . .

## Problem:

Gauge fields  $Z, W^+, W^-$  are **massive**

explicite mass terms in the Lagrangian  $\Leftrightarrow$  breaking of gauge invariance

## Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

## Higgs sector in the Standard Model:

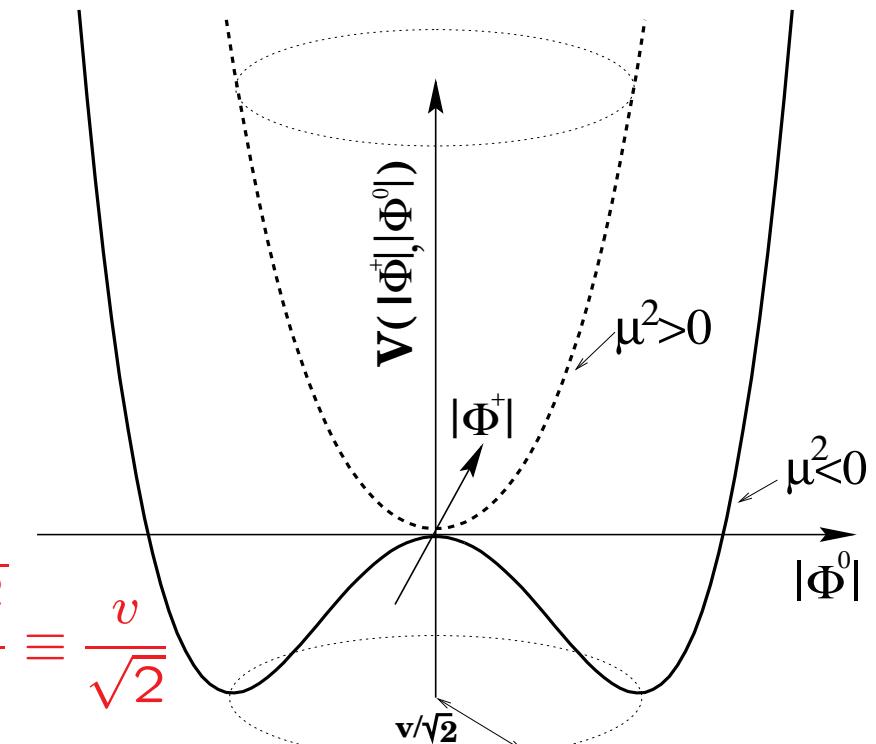
$$\text{Scalar SU(2) doublet: } \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Higgs potential:

$$V(\phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2, \quad \lambda > 0$$

$\mu^2 < 0$ : Spontaneous symmetry breaking

minimum of potential at  $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (\text{unitary gauge})$$

$H$ : elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R - g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

with

$$\begin{aligned} iD_\mu &= i\partial_\mu - g_2 \vec{I} \vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^* \qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

⇒ mass terms for gauge bosons and fermions

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle
2. measure its mass ( $\Rightarrow$  ok?)

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle
2. measure its mass ( $\Rightarrow$  ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle
2. measure its mass ( $\Rightarrow$  ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle
2. measure its mass ( $\Rightarrow$  ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

## Discovering the Higgs boson

### What has to be done?

1. Find the new particle L
2. measure its mass ( $\Rightarrow$  ok?) L
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

L = possible at the LHC

# Discovering the Higgs boson

## What has to be done?

1. Find the new particle L
2. measure its mass ( $\Rightarrow$  ok?) L
3. measure coupling to gauge bosons L
4. measure couplings to fermions L
5. measure self-couplings
6. measure spin, . . .

L = possible at the LHC

L = partially possible at the LHC

# Discovering the Higgs boson

## What has to be done?

1. Find the new particle L
2. measure its mass ( $\Rightarrow$  ok?) L
3. measure coupling to gauge bosons L
4. measure couplings to fermions L
5. measure self-couplings L
6. measure spin, . . . L

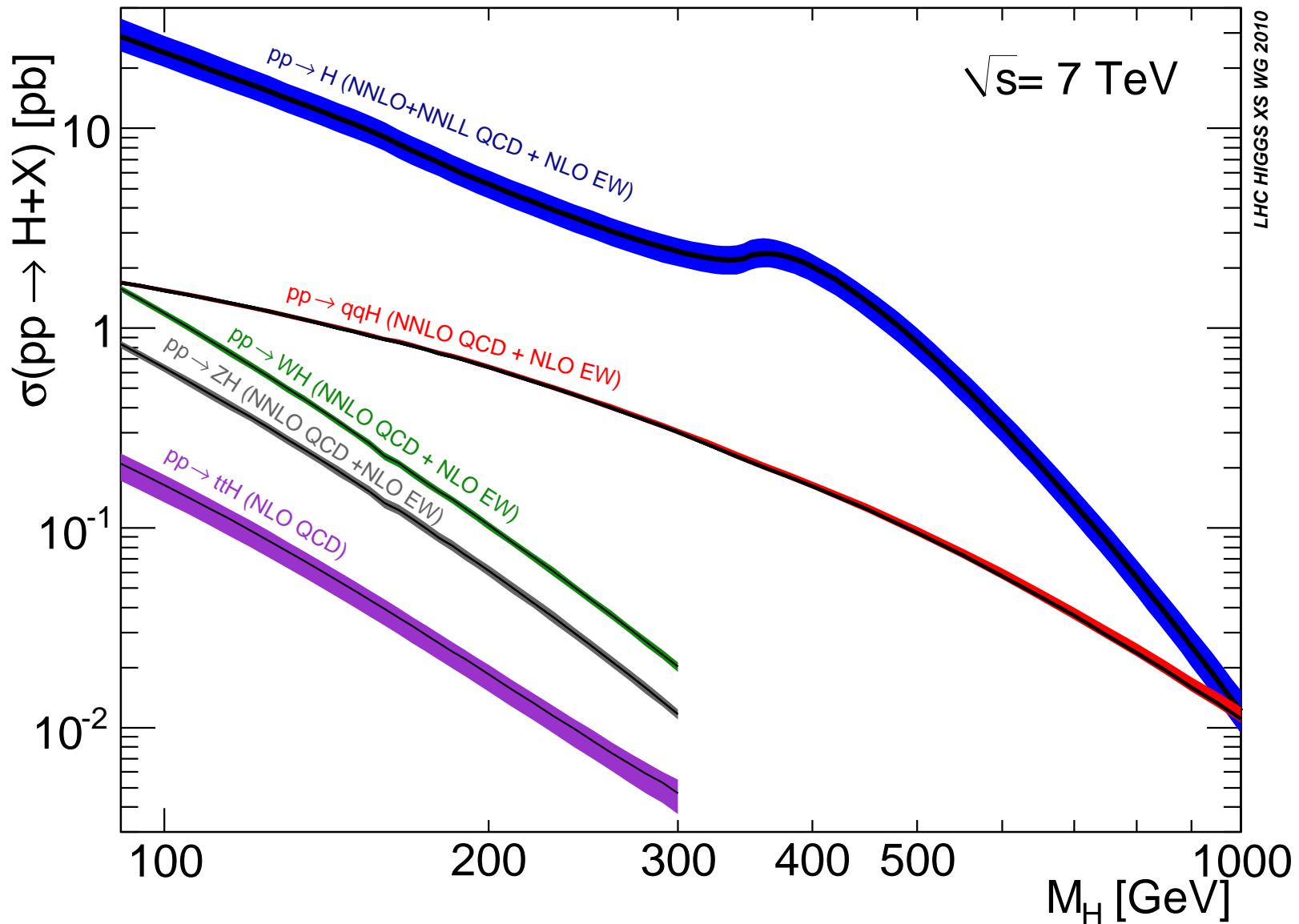
L = possible at the LHC

L = partially possible at the LHC

L = LHC perspective unclear

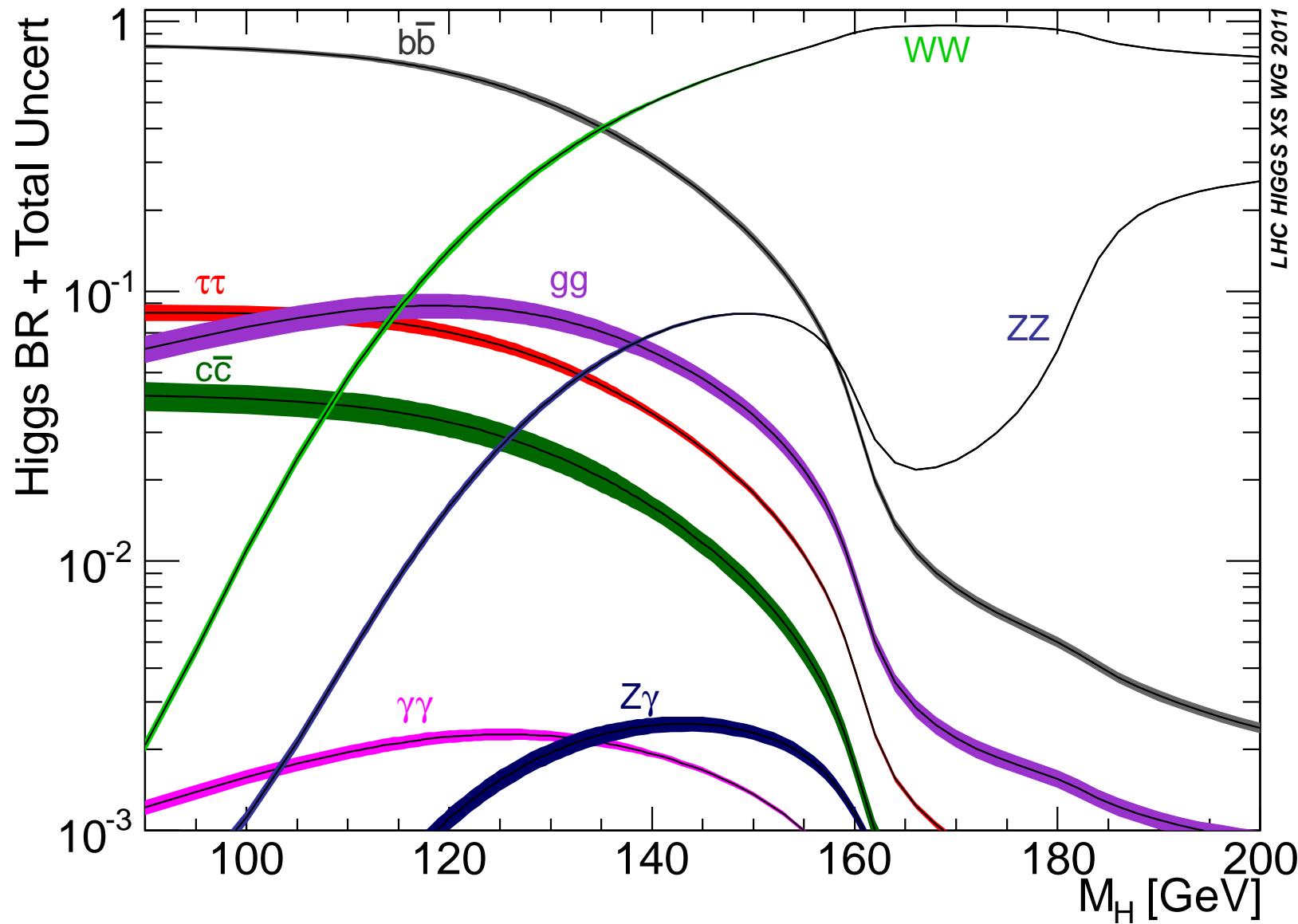
# Latest theory predictions for the SM Higgs: LHC production XS

[LHC Higgs XS WG '10 – '12]

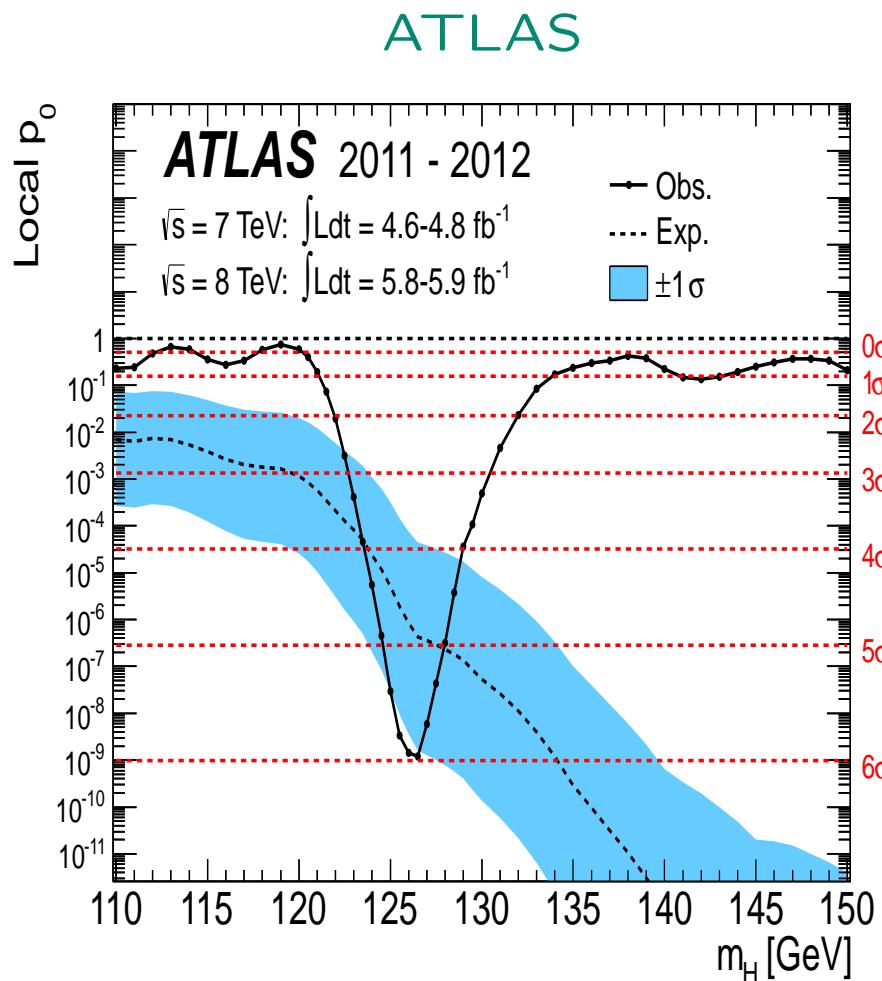


## Latest theory predictions for the SM Higgs: branching ratios

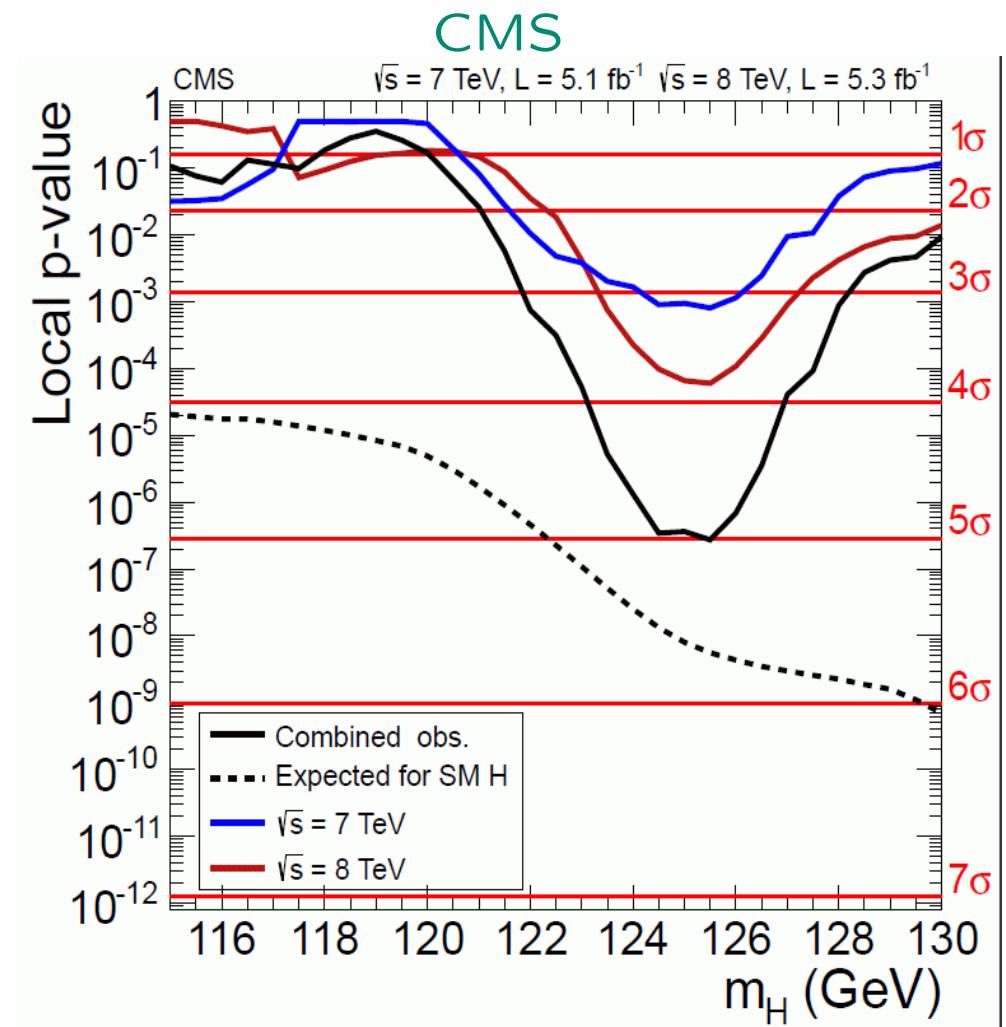
[LHC Higgs XS WG '10 – '12]



## Results from 04.07.2012:



$$M_H = 126.0 \pm 0.4 \pm 0.4 \text{ GeV}$$



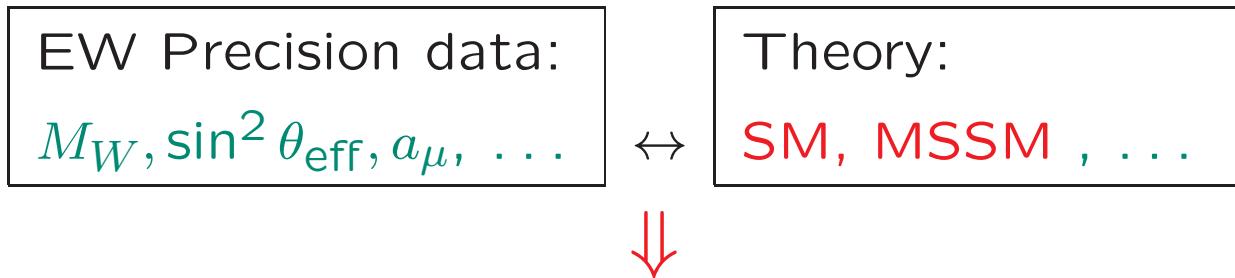
$$M_H = 125.3 \pm 0.5 \pm 0.4 \text{ GeV}$$

## 2. Implications for the SM

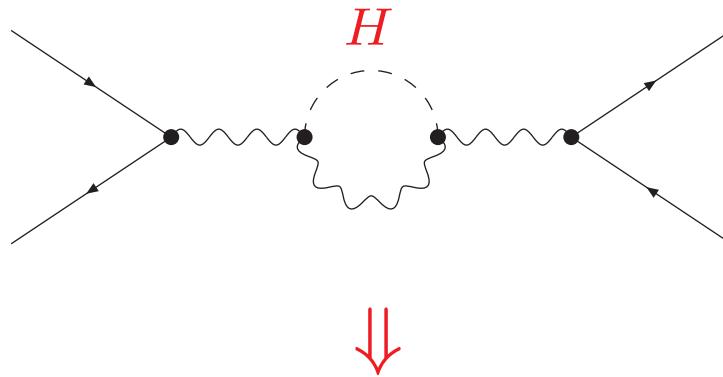
How did we make predictions for the SM Higgs mass before observation?

## 2. Implications for the SM

Comparison of electro-weak precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections, e.g.  $H$



SM: limits on  $M_H$

Very high accuracy of measurements and theoretical predictions needed

## Example: prediction of $M_W$

Theoretical prediction for  $M_W$  in terms of  $M_Z, \alpha, G_\mu, \Delta r$ :

$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

⇓  
loop corrections

Evaluate  $\Delta r$  from  $\mu$  decay  $\Rightarrow M_W$

One-loop result for  $M_W$  in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\begin{aligned} \Delta r_{\text{1-loop}} &= \Delta \alpha - \frac{c_W^2}{s_W^2} \Delta \rho + \Delta r_{\text{rem}}(M_H) \\ &\sim \log \frac{M_Z}{m_f} \quad \sim m_t^2 \quad \log(M_H/M_W) \\ &\sim 6\% \quad \sim 3.3\% \quad \sim 1\% \end{aligned}$$

## Comparison of SM prediction of $M_W$ with direct measurements:

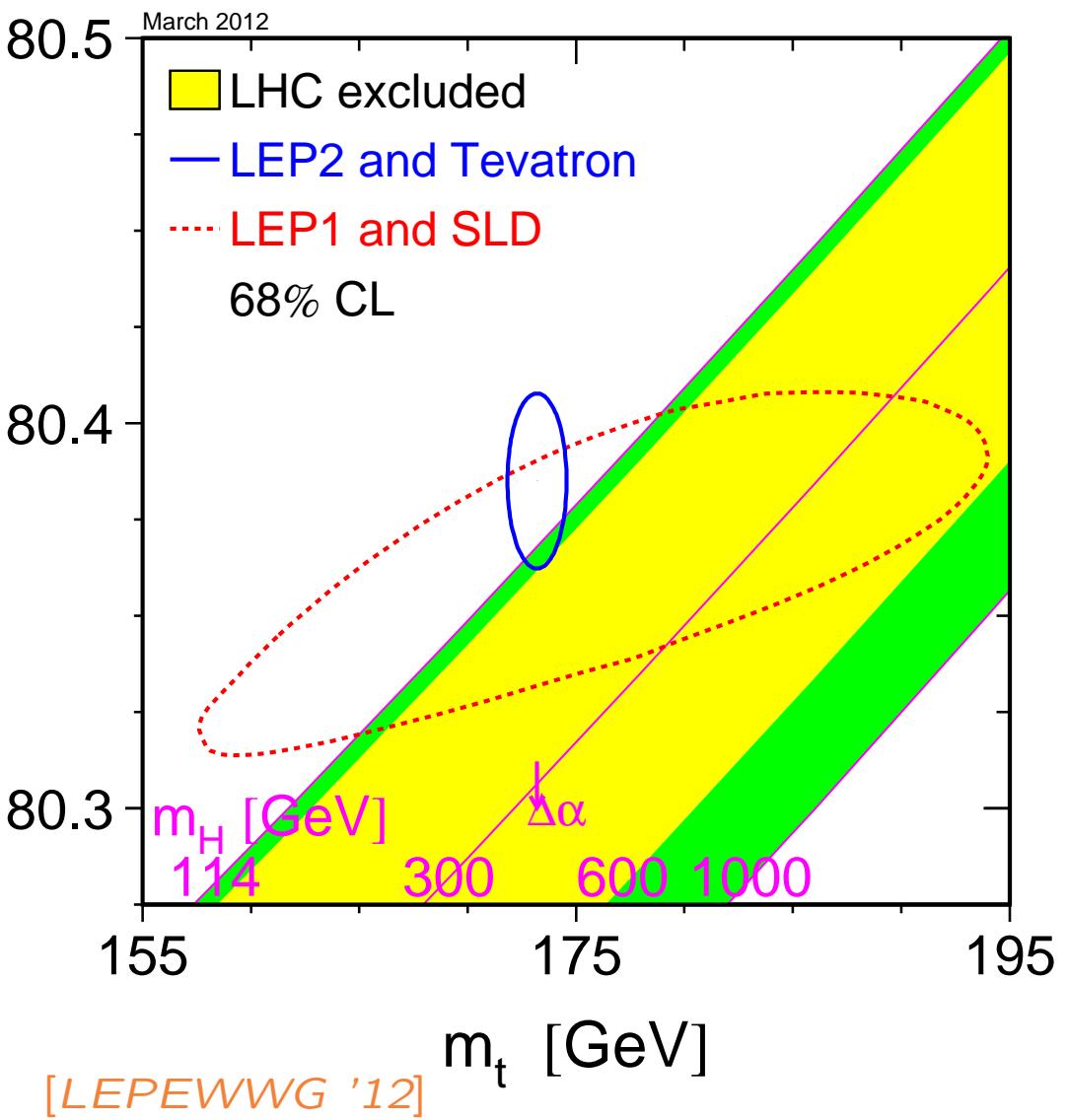
$$\Delta r = -\frac{11g_2^2}{96\pi^2} \frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[ \log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2} \right]$$

leading term:  $\log(M_H)$

first term  $\sim M_H^2$  with  $g_2^4$



⇒ light Higgs boson preferred

## Indirect prediction vs. “the discovery”:

[LEPEWWG '12]

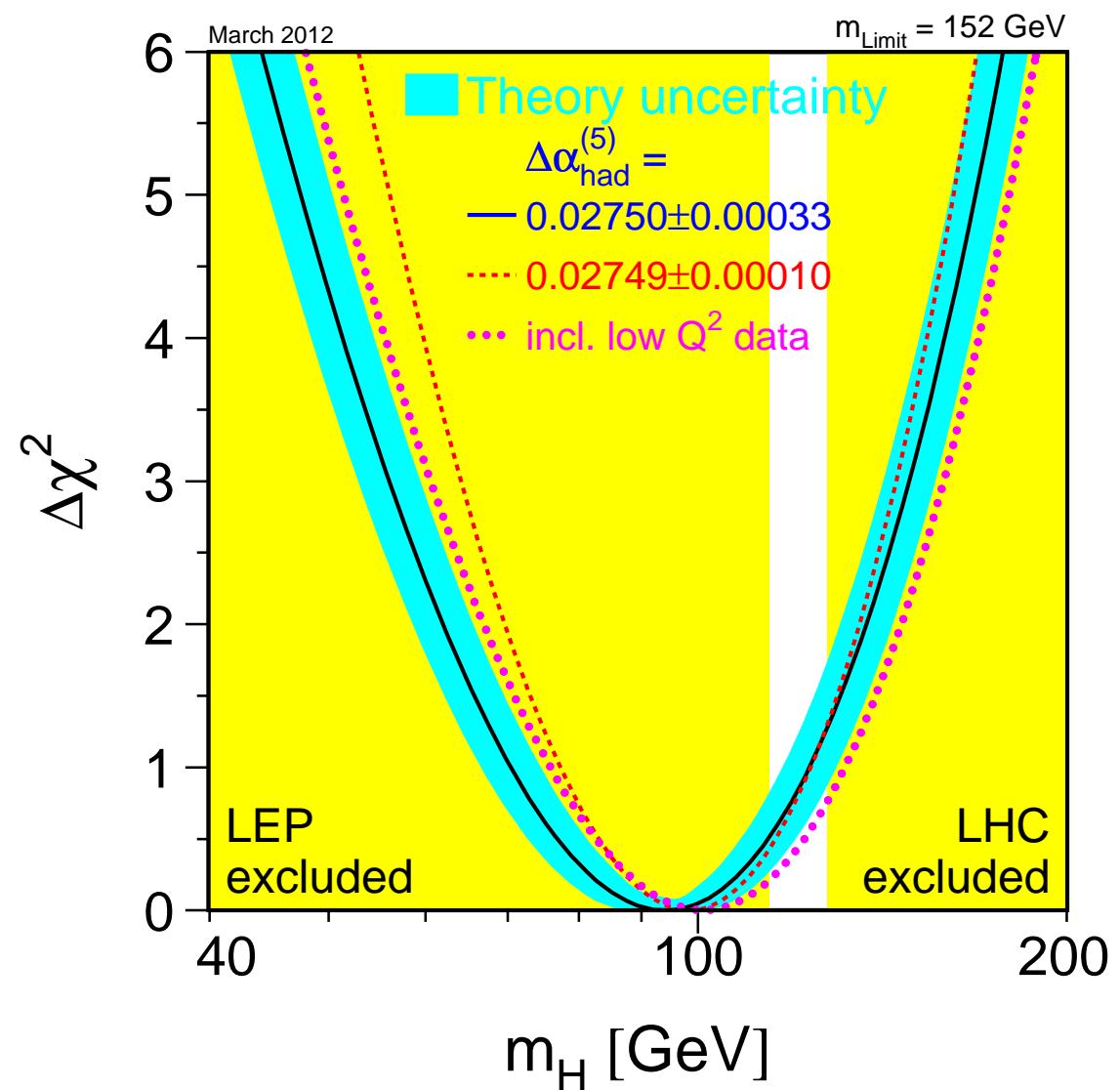
$$\Rightarrow M_H = 94^{+29}_{-24} \text{ GeV}$$

$$M_H < 152 \text{ GeV, 95% C.L.}$$

Assumption for the fit:

SM incl. Higgs boson

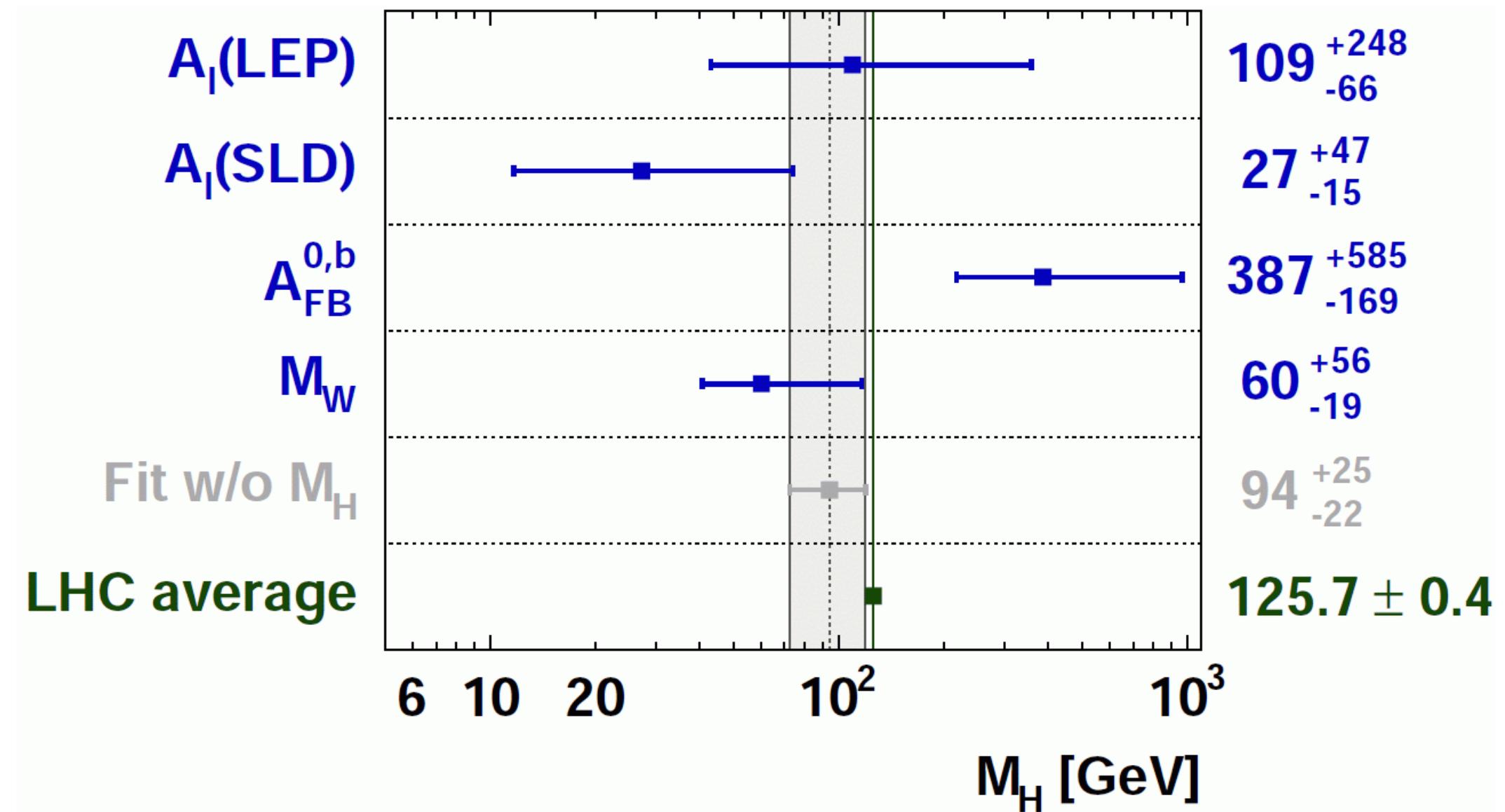
$\Rightarrow$  no confirmation of  
Higgs mechanism



$\Rightarrow$  Observed excess well compatible with SM prediction

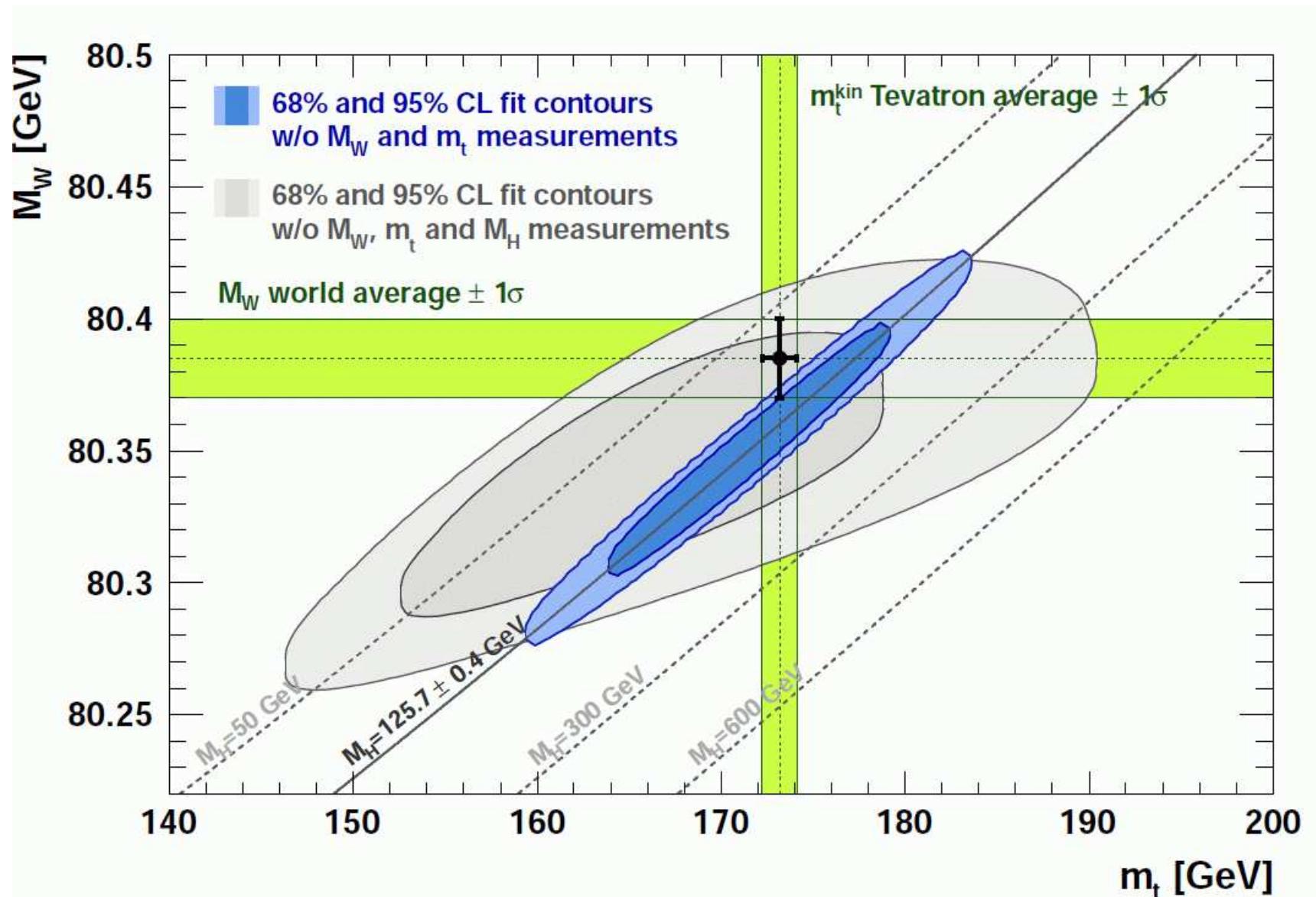
## Comparison for single observables:

[*GFitter '12*]



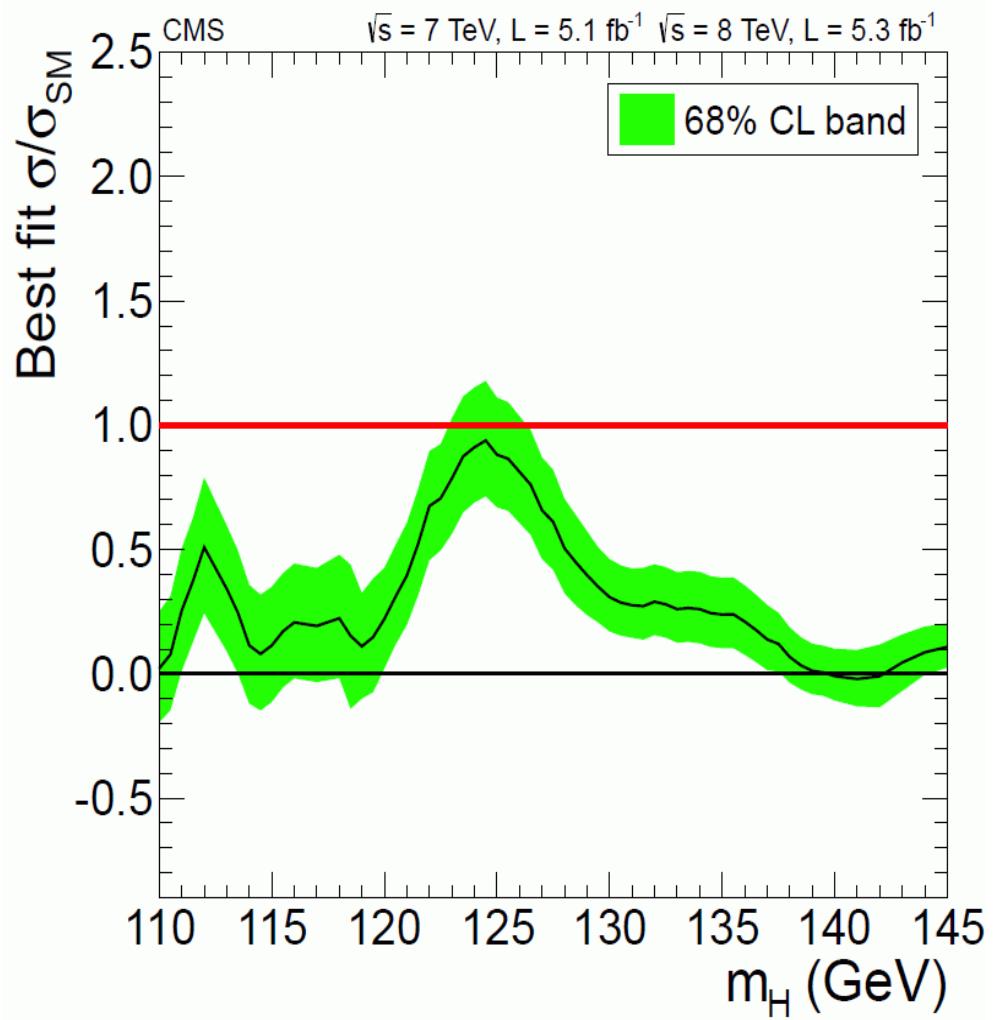
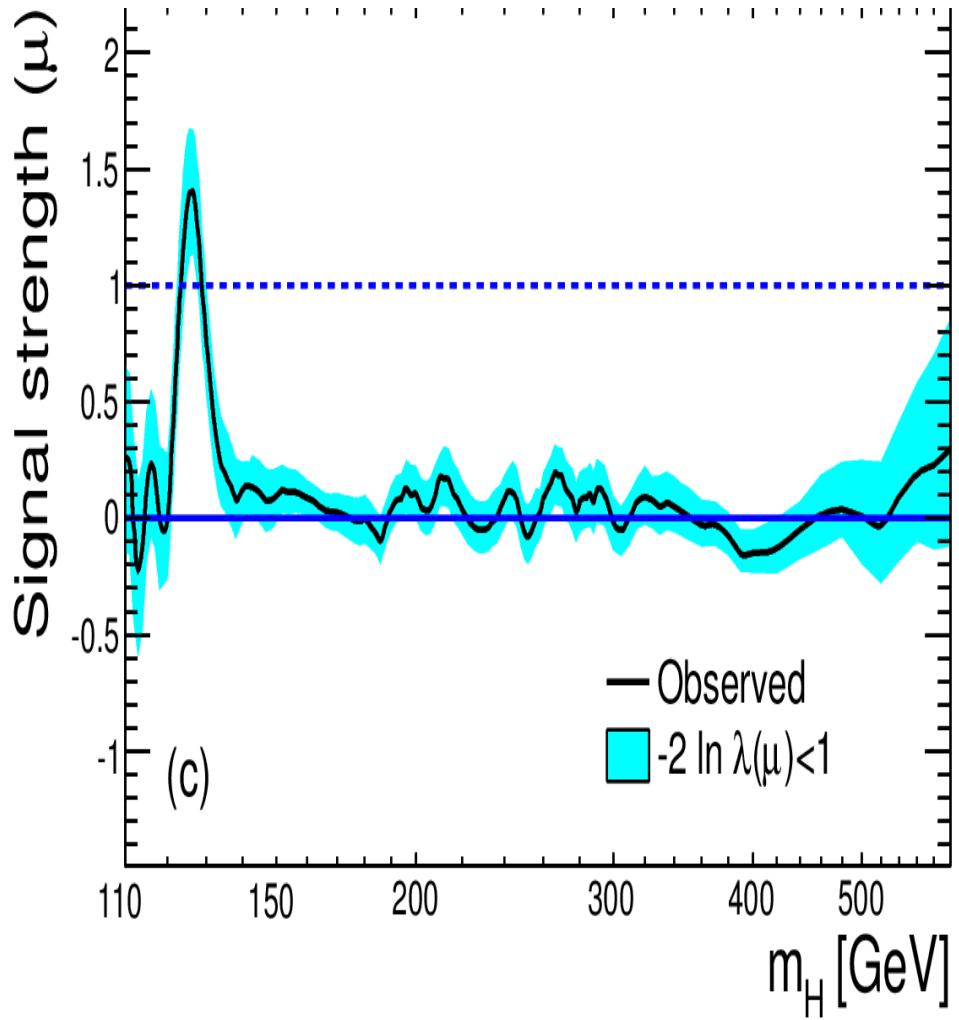
## Comparison for $M_W$ and $m_t$ :

[GFitter '12]



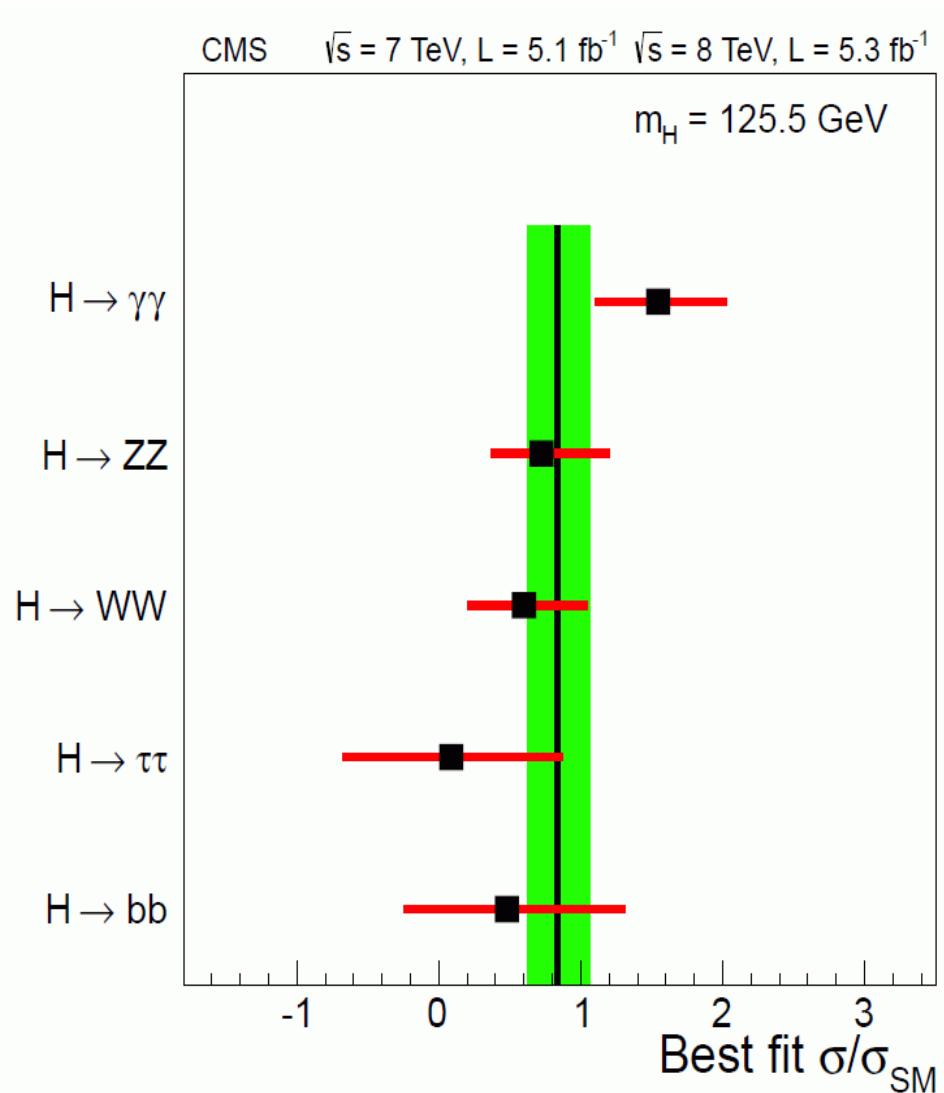
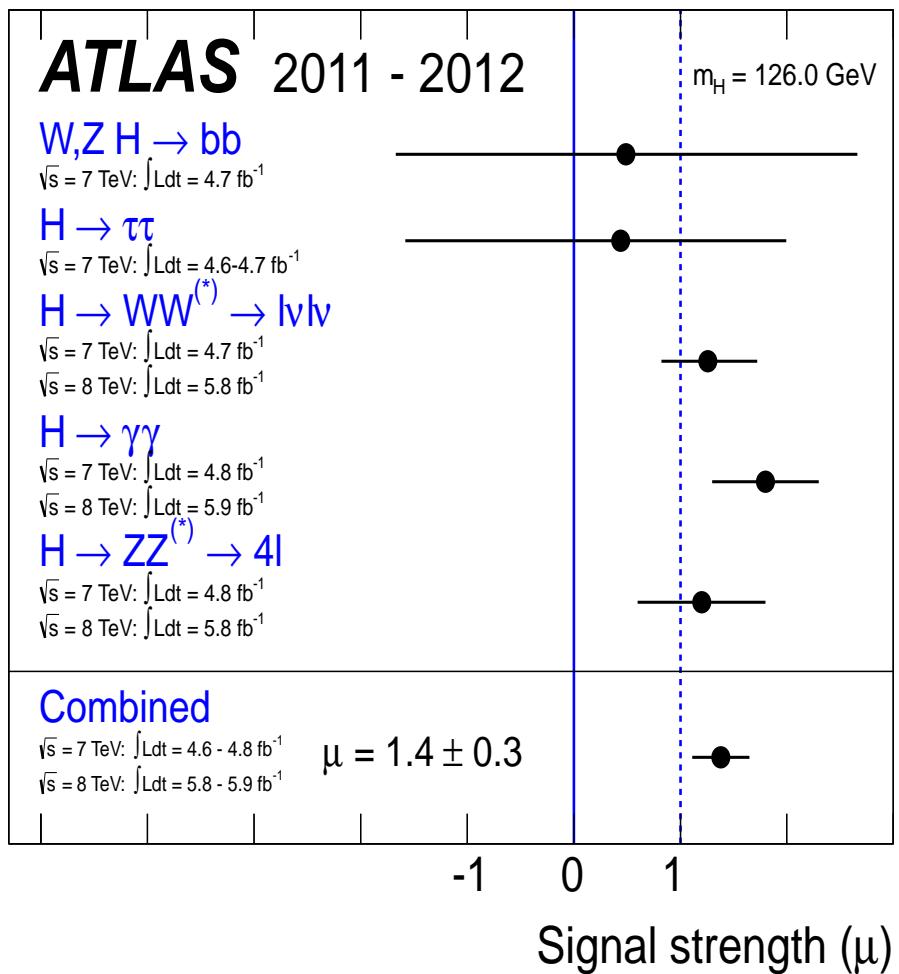
### 3. Towards a coupling determination

Signal strength:



⇒ looks well compatible with the SM Higgs!

## More information: single channel signal strength:



Note: always  $\sigma \times BR$

How to use this information?

## LHC Higgs Cross Section Working Group: Low Mass (LM) subgroup:

### Assumptions (for 2012 data):

1. Signal corresponds to only one state, no overlapping signal etc.
2. Zero-width approximation
3. Only modification of **coupling strength** (absolute values of couplings) but not of **tensore structure** wrt. to SM

### Recommendations (for 2012 data):

1. Use state-of-the-art predictions in the SM and rescale the predictions with “**leading order inspired**” scale factors  $\kappa_i$   
( $\kappa_i = 1$  corresponds to the SM case)
2. Most general case:  $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \dots \oplus$  extra loop contributions to  $\sigma(gg \rightarrow H), \Gamma(H \rightarrow gg), \Gamma(H \rightarrow \gamma\gamma), \Gamma_{H,\text{tot}}$
3. **benchmarks:**
  - one parameter: overall signal strength  $\kappa \equiv \mu$
  - two parameters:  $\kappa_V := \kappa_W = \kappa_Z, \kappa_F := \kappa_t = \kappa_b = \kappa_\tau = \dots$
  - ...

## Recommendations continued:

Total width  $\Gamma_{H,\text{tot}}$  cannot be measured without further theory assumptions.

(This is not a recommendation, but a fact!)

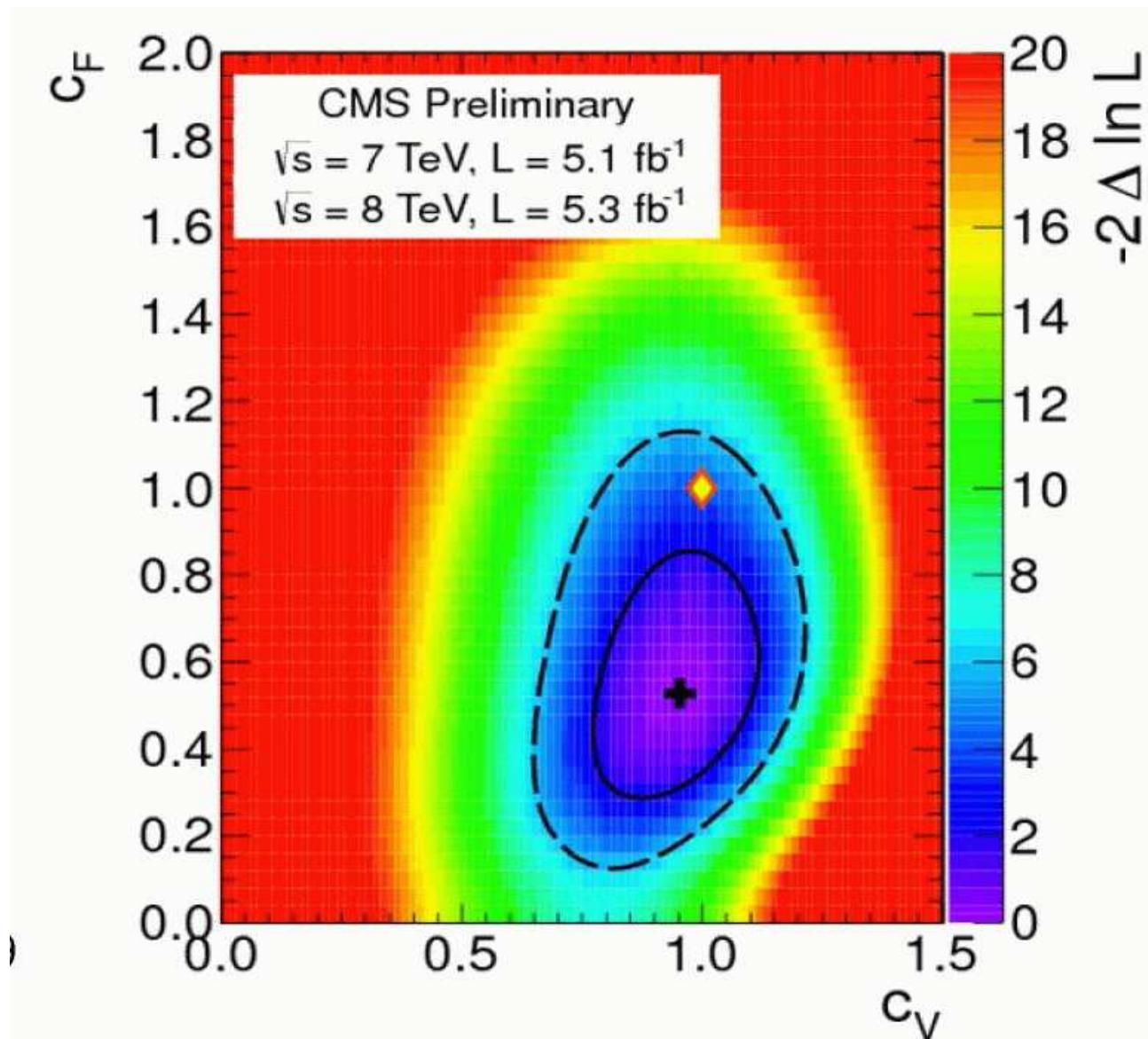
For each benchmark (except overall coupling strength) two versions are proposed:

with and without taking into account the possibility of additional contributions to the total width

- additional contributions to  $\Gamma_{H,\text{tot}}$  are allowed:  
⇒ Determination of ratios of scaling factors, e.g.  $\kappa_i \kappa_j / \kappa_H$
- no additional contributions to  $\Gamma_{H,\text{tot}}$  are allowed:  
⇒ Determination of  $\kappa_i$  (evaluated to NLO QCD accuracy)

## Example of application (I):

[CMS '12]



Note:  $\chi^2/\text{d.o.f.}$  excellent already in SM!

$$g_x = g_x^{\text{SM}} (1 + \Delta_x)$$

**Fit 1:**

One coupling modifier for everything:  $\Delta_H$

**Fit 2:**

One for gauge bosons,  $\Delta_V$ , one for fermions,  $\Delta_f$

**Fit 3:**

Fit individual couplings:  $\Delta_W$ ,  $\Delta_Z$ ,  $\Delta_t$ ,  $\Delta_b$ ,  $\Delta_\tau$

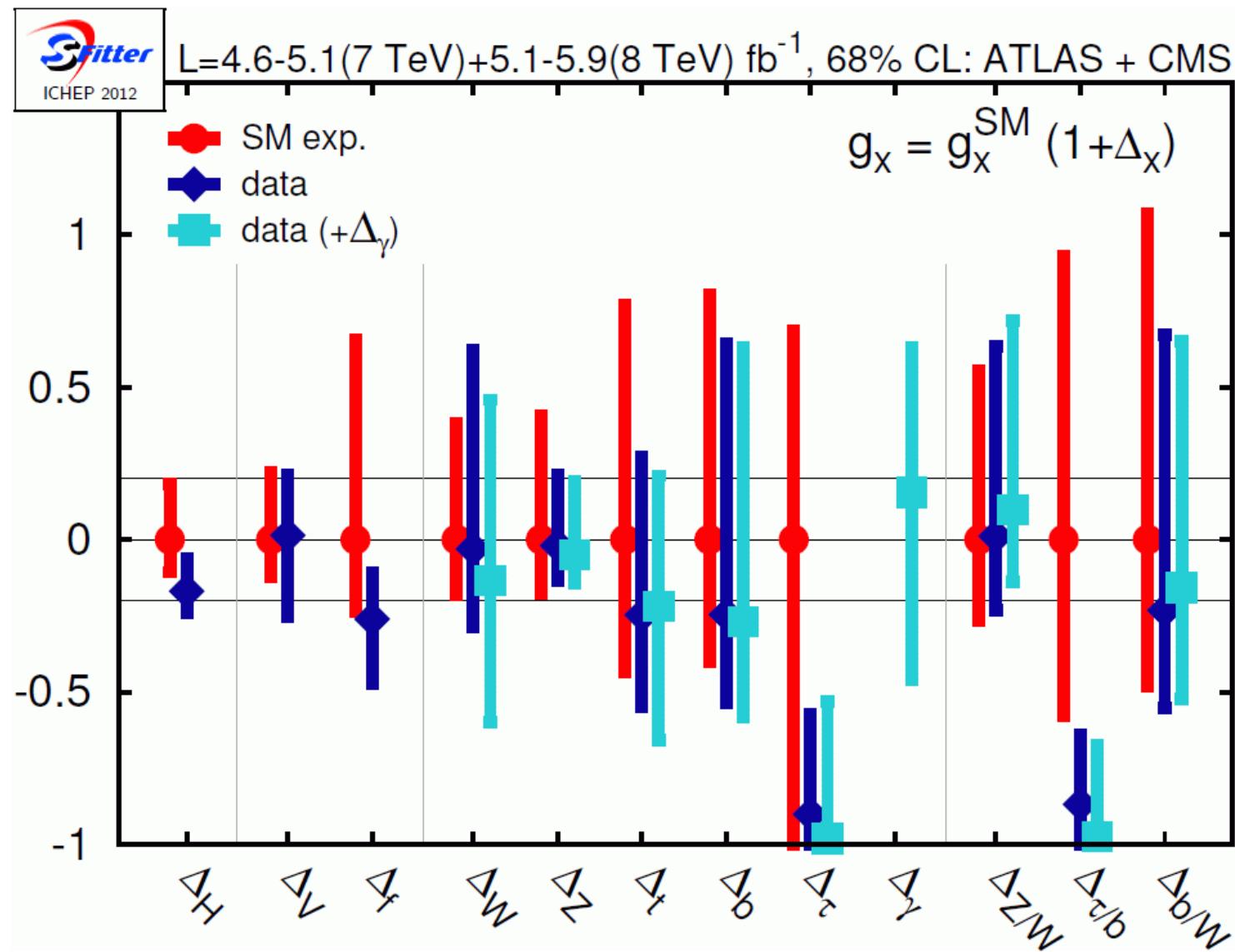
⇒ theory assumptions on total width necessary!

**Fit 4:**

Allow additionally loop contributions in  $H \rightarrow \gamma\gamma$ :  $\Delta_\gamma$

## Coupling fits from SFitter:

[SFitter '12]



⇒ no deviation from the SM observed (within the uncertainties)

## 4. Implications in the MSSM:

SUSY: Symmetry between

Bosons  $\leftrightarrow$  Fermions

$$Q \text{ |Fermion} \rangle \rightarrow \text{|Boson} \rangle$$

$$Q \text{ |Boson} \rangle \rightarrow \text{|Fermion} \rangle$$

Simplified examples:

$$Q \text{ |top, } t \rangle \rightarrow \text{|scalar top, } \tilde{t} \rangle$$

$$Q \text{ |gluon, } g \rangle \rightarrow \text{|gluino, } \tilde{g} \rangle$$

$\Rightarrow$  each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality:  $m_e \neq m_{\tilde{e}}$   $\Rightarrow$  SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy:  $M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$

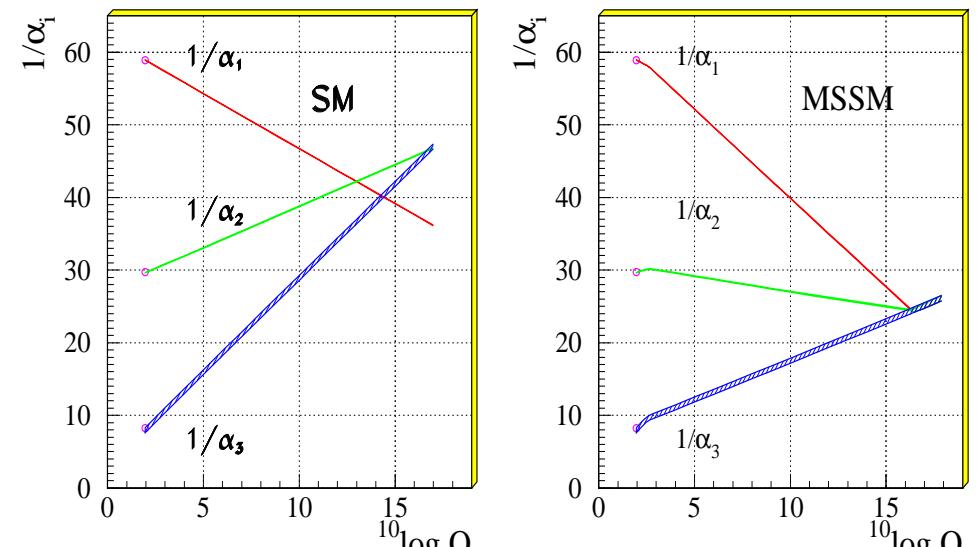
## Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

- 1.) Stability of the Higgs mass against higher-order corr.
- 2.) Unification of gauge couplings:  
Not possible in the SM, but in the **MSSM** (although it was **not** designed for it.)
- 3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in **SUSY GUTs**
- 4.) SUSY provides CDM candidate
- 5.) ...

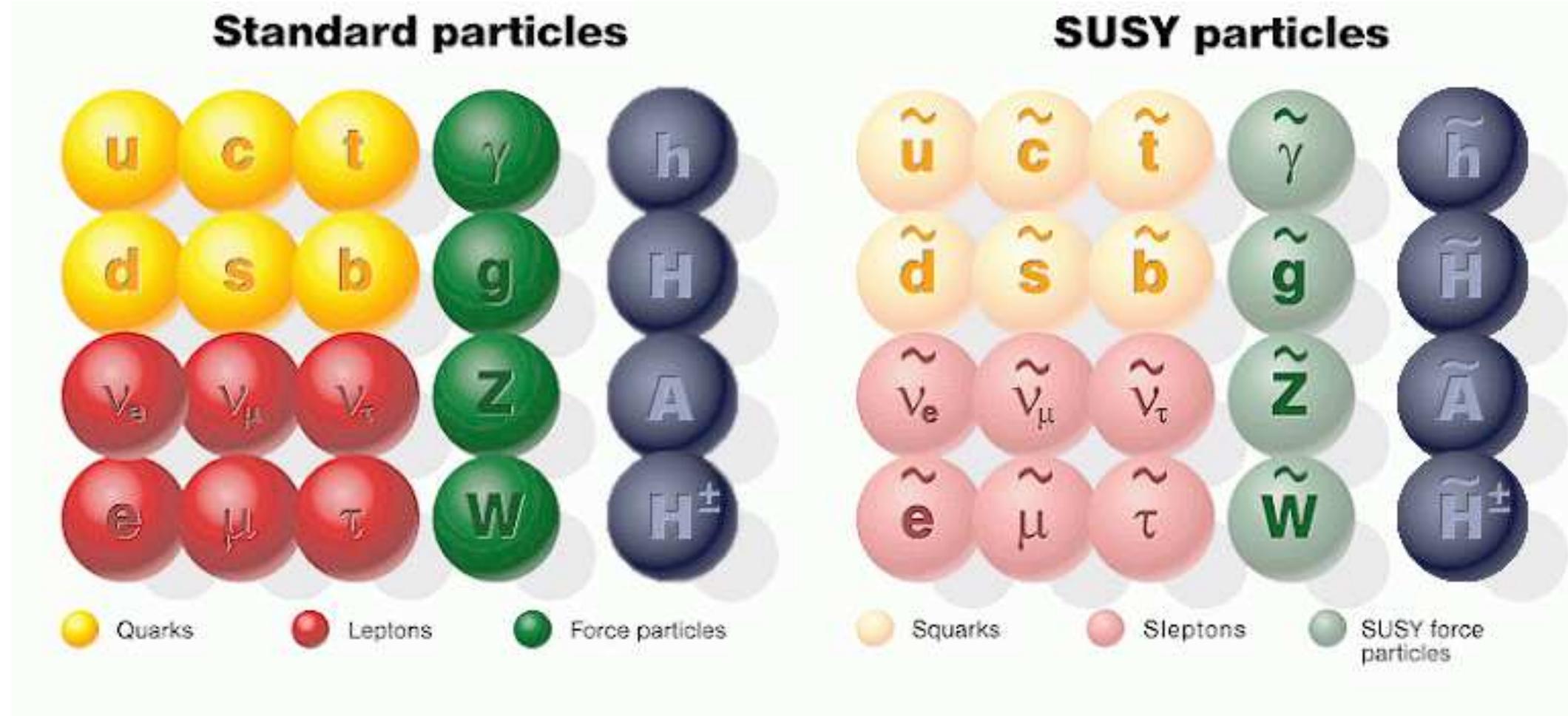
Unification of the Coupling Constants in the SM and the minimal MSSM



[Amaldi, de Boer, Fürstenau '92]

# The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



## Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{}} |H_1 \bar{H}_2|^2$$

$\Rightarrow m_h \leq M_Z$

physical states:  $h^0, H^0, A^0, H^\pm$

Goldstone bosons:  $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

## The lightest MSSM Higgs boson

MSSM predicts upper bound on  $M_h$ :

tree-level bound:  $m_h < M_Z$ , excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings:  $\frac{e m_t}{2 M_W s_W}$ ,  $\frac{e m_t^2}{M_W s_W}$ , ...

⇒ Dominant one-loop corrections:  $\Delta M_h^2 \sim G_\mu m_t^4 \log \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

The MSSM Higgs sector is connected to all other sector via loop corrections  
(especially to the scalar top sector)

Present status of  $M_h$  prediction in the MSSM:

Complete one-loop and ‘almost complete’ two-loop result available

## Upper bound on $M_h$ in the MSSM:

“Unconstrained MSSM”:

$M_A$ ,  $\tan \beta$ , 5 parameters in  $\tilde{t}$ – $\tilde{b}$  sector,  $\mu$ ,  $m_{\tilde{g}}$ ,  $M_2$

$$M_h \lesssim 135 \text{ GeV}$$

for  $m_t = 173.2 \pm 0.9 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)

⇒ observable at the LHC

Obtained with:

FeynHiggs

[www.feynhiggs.de](http://www.feynhiggs.de)

[T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein (K. Williams) '98 – '12]

→ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

## Upper bound on $M_h$ in the MSSM:

“Unconstrained MSSM”:

$M_A$ ,  $\tan \beta$ , 5 parameters in  $\tilde{t}$ – $\tilde{b}$  sector,  $\mu$ ,  $m_{\tilde{g}}$ ,  $M_2$

$$M_h \lesssim 135 \text{ GeV}$$

Note :  $125 < 135!$

for  $m_t = 173.2 \pm 0.9 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)

⇒ observable at the LHC

Obtained with:

FeynHiggs

[www.feynhiggs.de](http://www.feynhiggs.de)

[T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein (K. Williams) '98 – '12]

→ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

## The decoupling limit:

For  $M_A \gtrsim 150$  GeV:

The lightest MSSM Higgs  
is SM-like

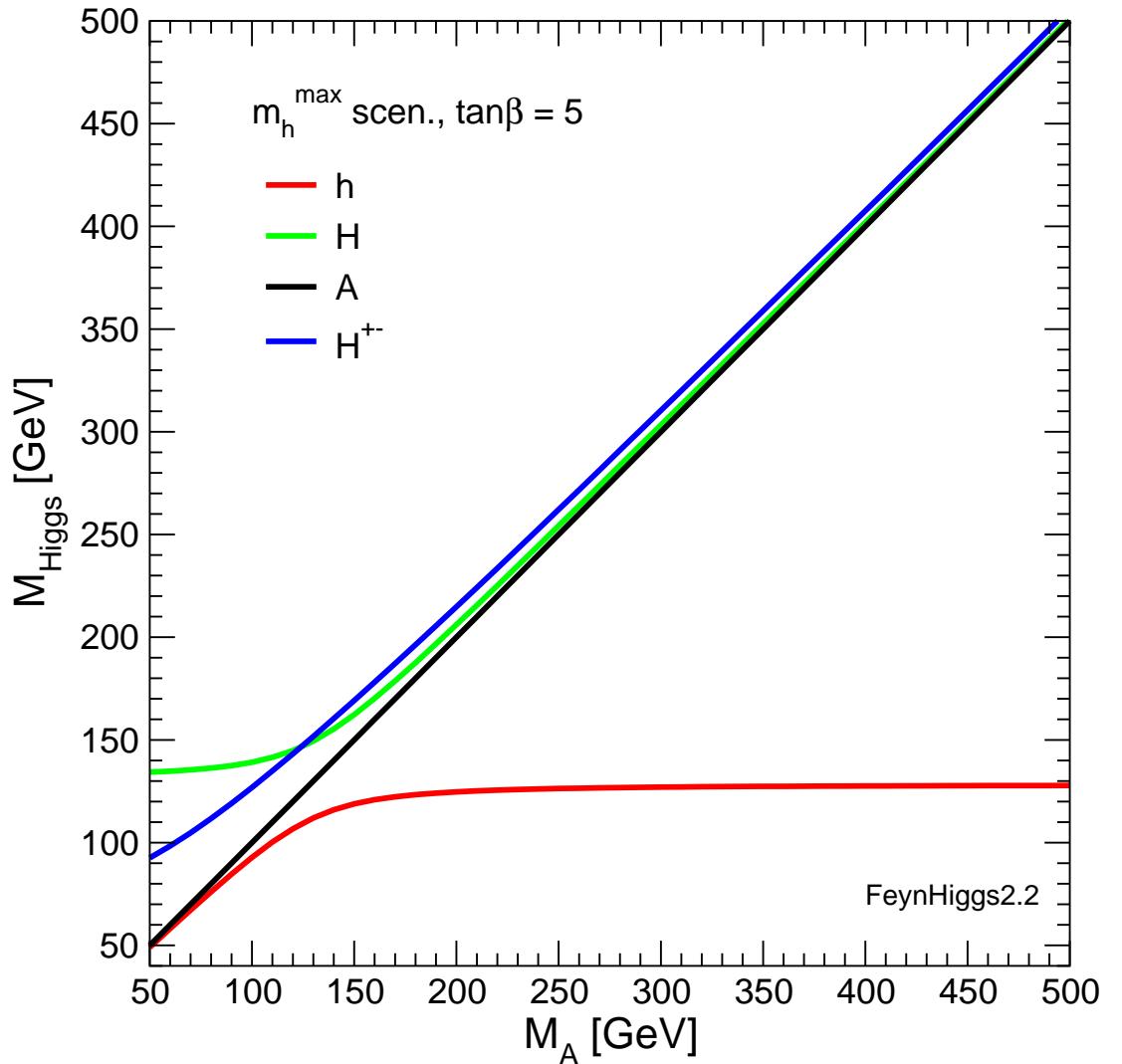
→ SM analysis applies!

The heavy MSSM Higgses:

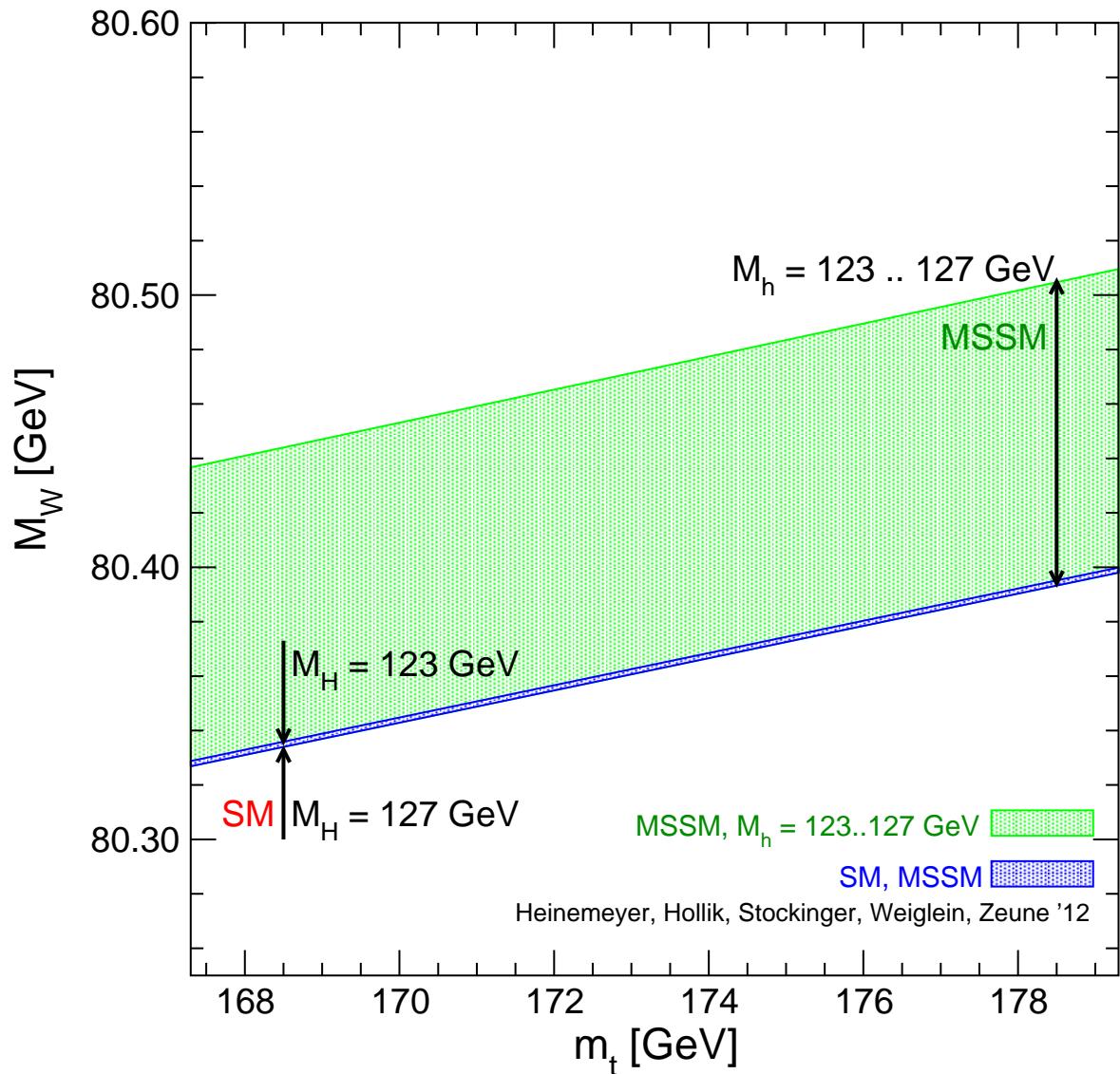
$M_A \approx M_H \approx M_{H^\pm}$

→ coupling to gauge bosons  $\sim 0$

→ no decay  $H \rightarrow WW^{(*)}, \dots$



Prediction for  $M_W$  in the **SM** and the **MSSM** :  
[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '12]



**MSSM band:**

scan over  
SUSY masses

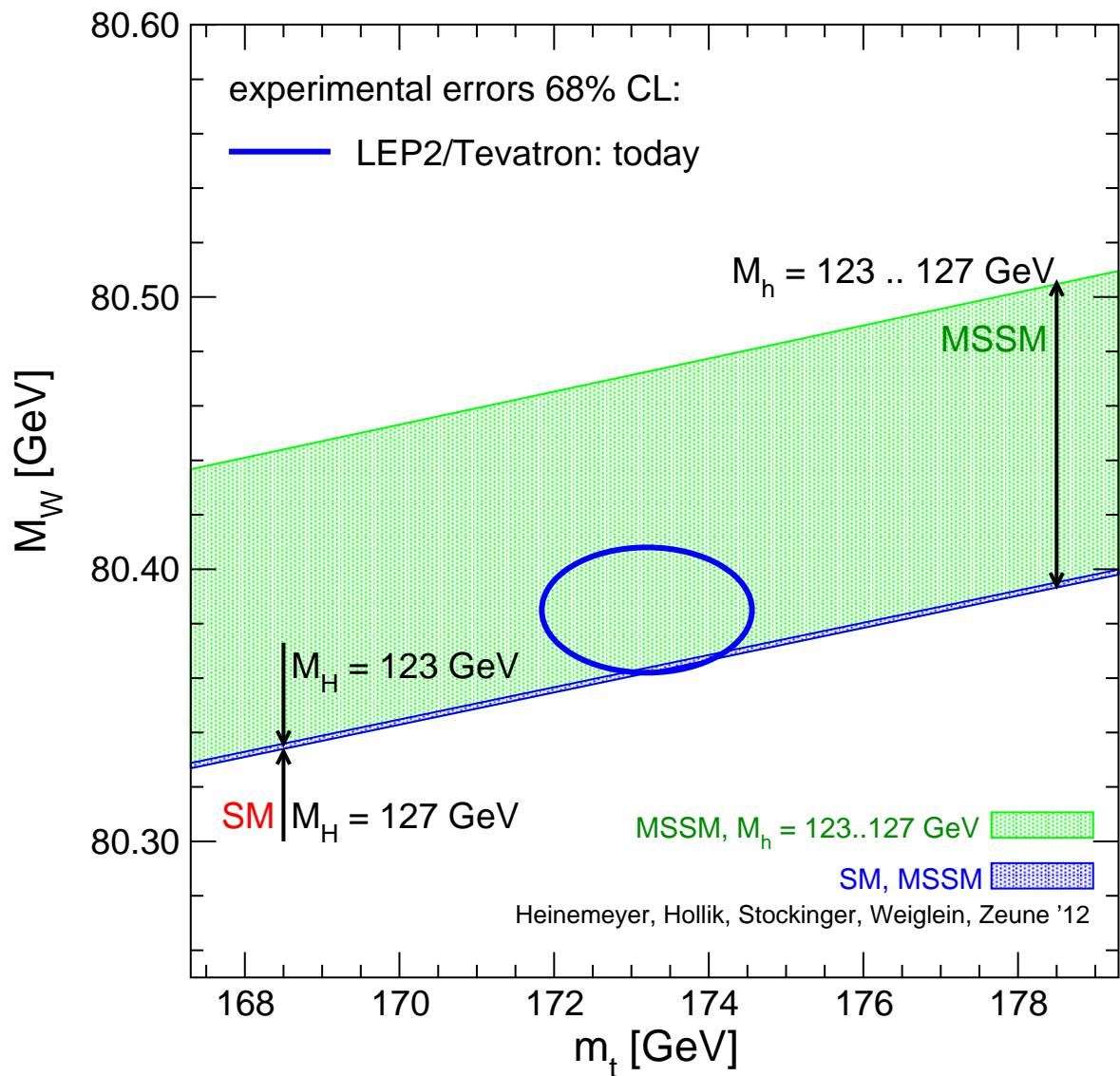
overlap:

SM is MSSM-like  
MSSM is SM-like

**SM band:**

variation of  $M_H^{\text{SM}}$

Prediction for  $M_W$  in the **SM** and the **MSSM** :  
[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '12]



**MSSM band:**

scan over  
SUSY masses

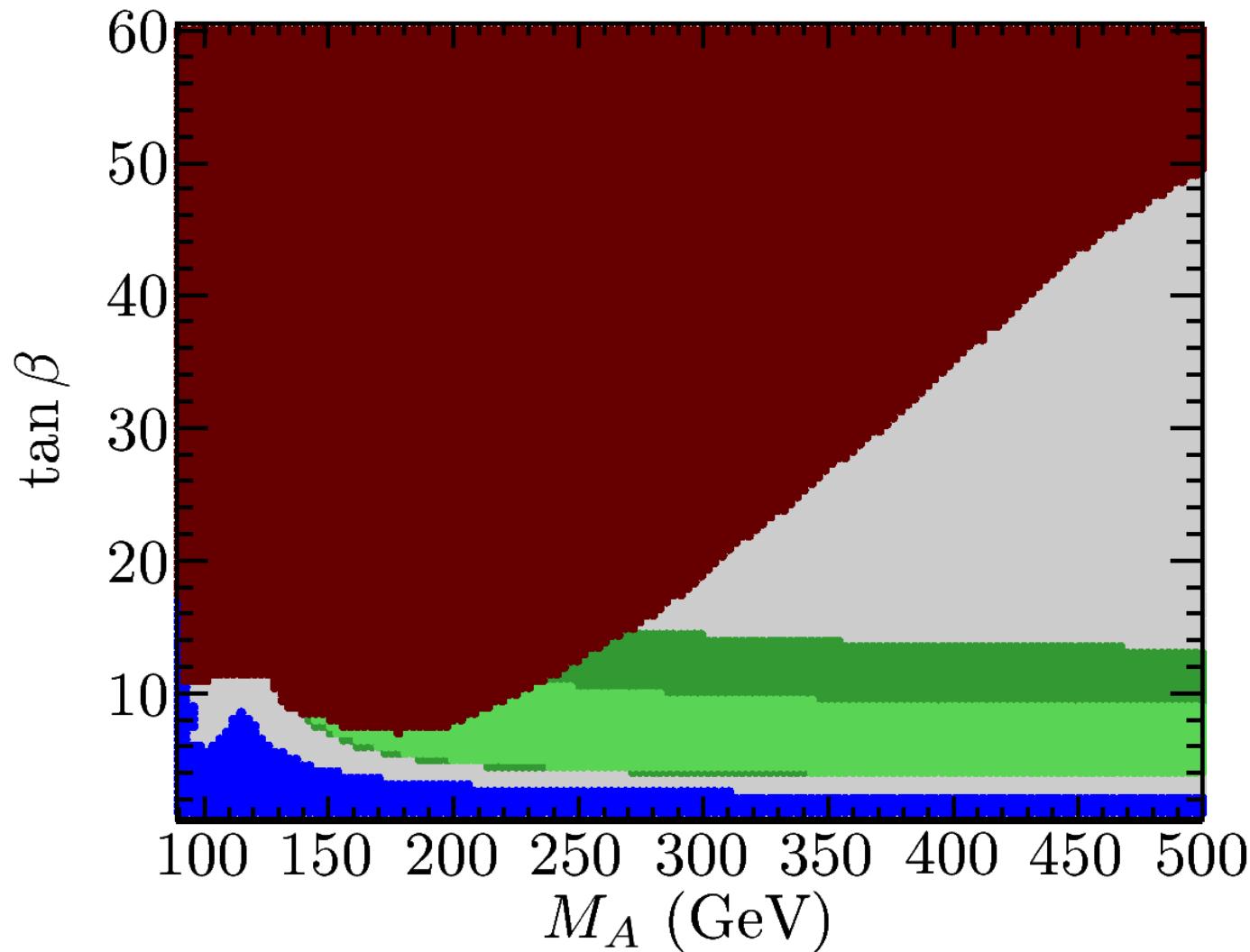
overlap:

SM is MSSM-like  
MSSM is SM-like

**SM band:**

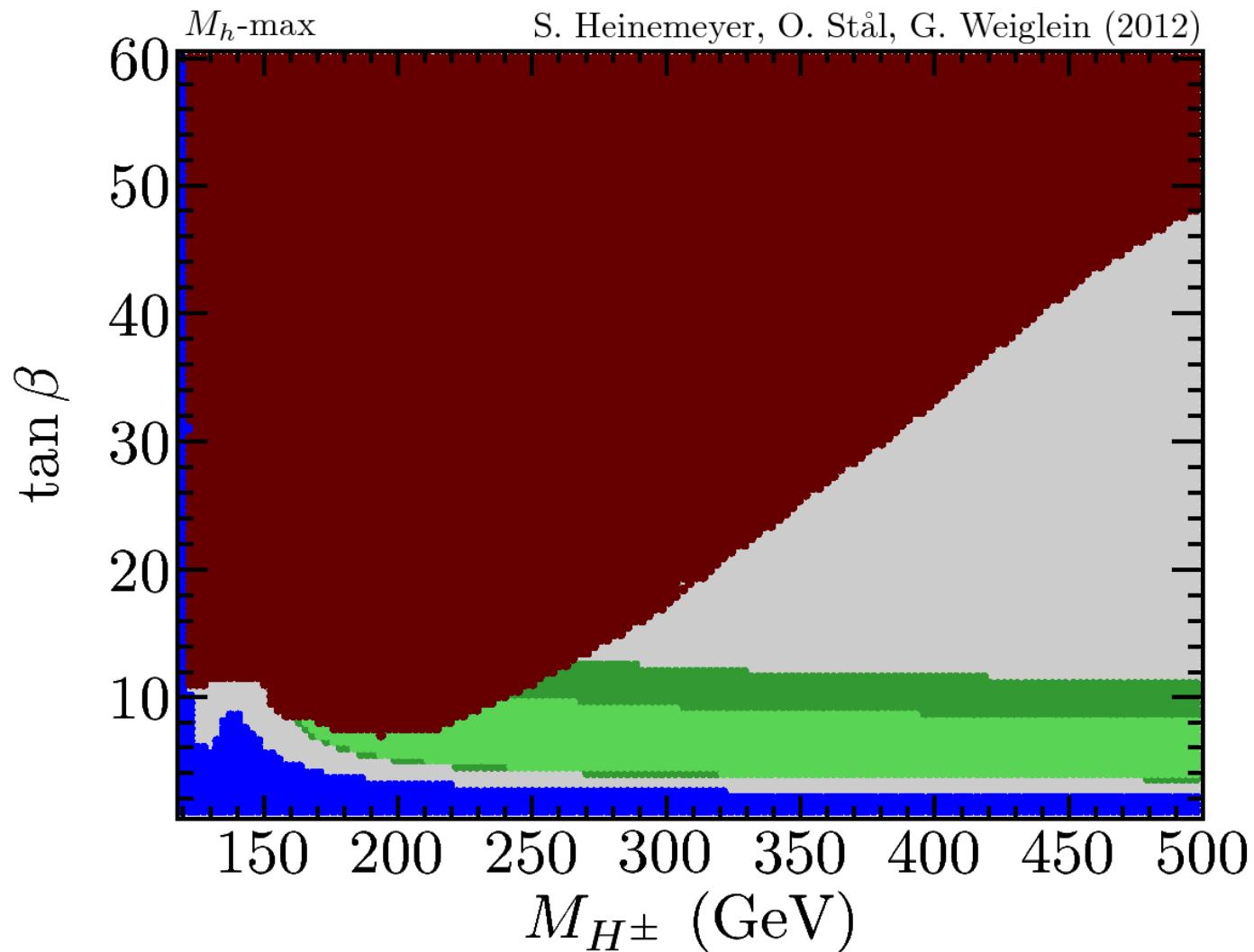
variation of  $M_H^{\text{SM}}$

⇒ maximize all contributions:  $m_h^{\max}$  scenario and assume  $M_h = 126 \pm 3$  GeV



⇒ new bounds:  $M_A > 140$  GeV,  $\tan \beta > 4$

⇒ maximize all contributions:  $m_h^{\max}$  scenario and assume  $M_h = 126 \pm 3$  GeV

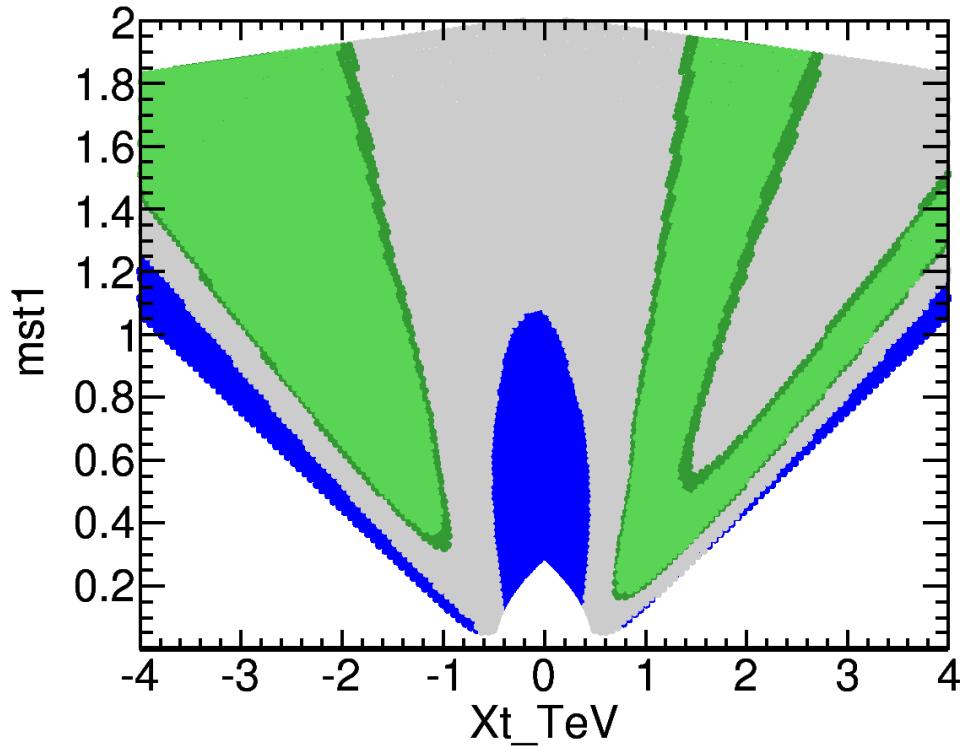
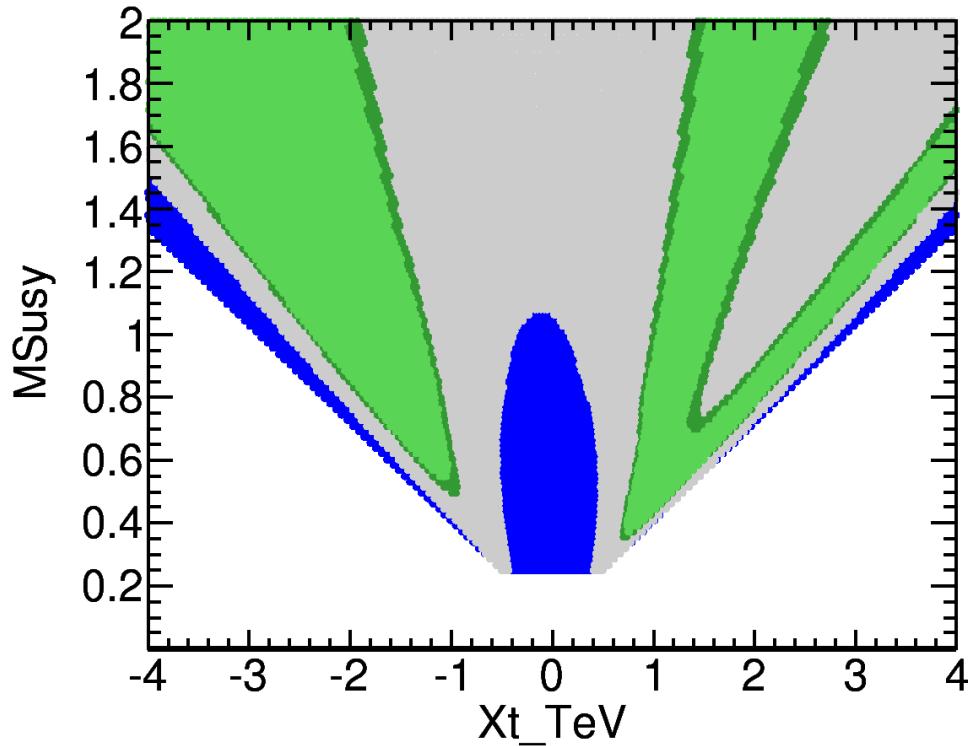


→ new bounds:  $M_{H^\pm} > 161$  GeV,  $\tan \beta > 4$  ⇒ light  $H^\pm$  window is closing

Limits on stop masses:

[S.H., O. Stal, G. Weiglein '11]

$m_h^{\max}$  scenario:

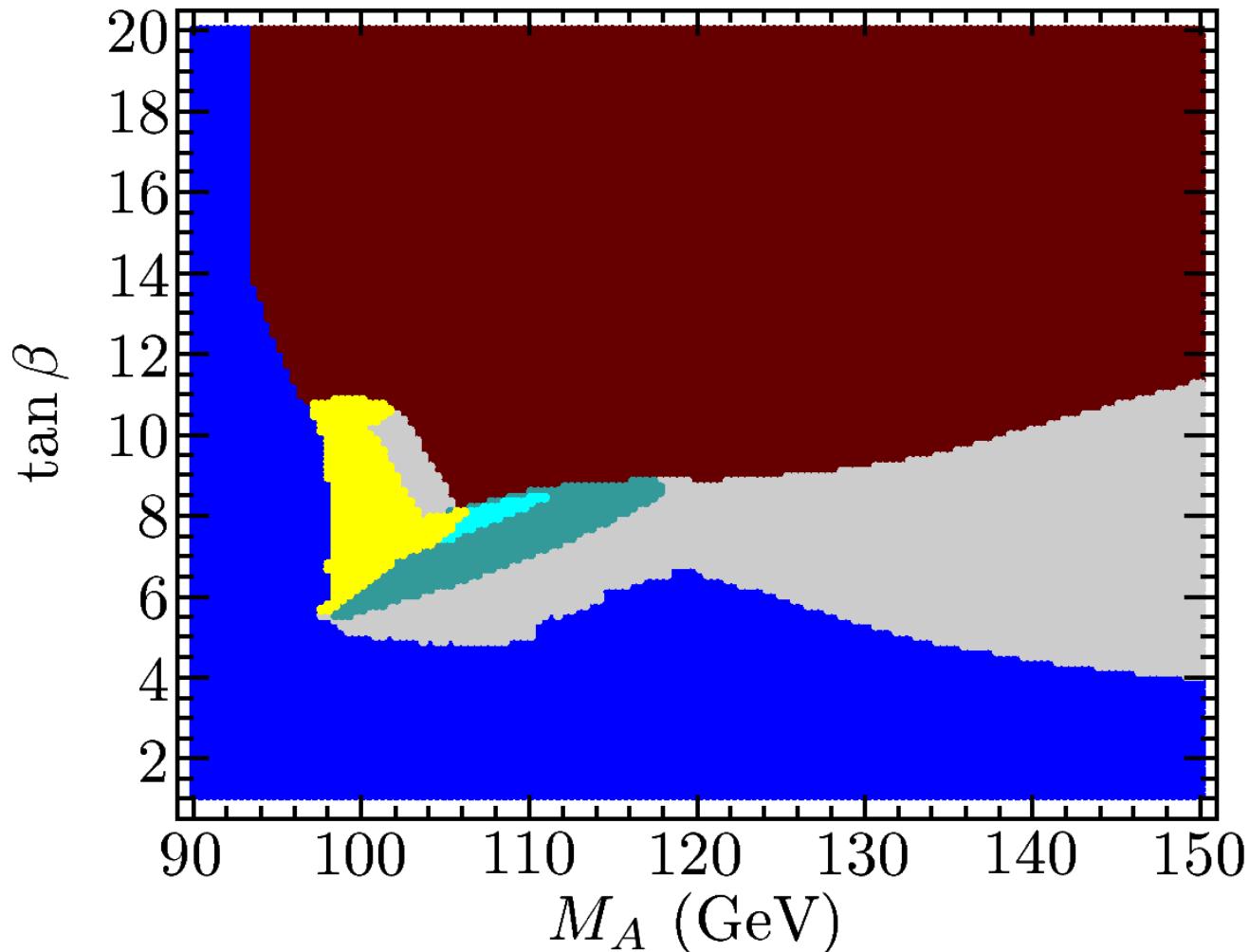


→ green are allowed by Higgs “excess”

$m_{\tilde{t}1} \gtrsim 150 \text{ GeV } (X_t > 0)$

$m_{\tilde{t}1} \gtrsim 300 \text{ GeV } (X_t < 0)$  (preferred by  $\text{BR}(b \rightarrow s\gamma)$ )

$M_{\text{SUSY}} = \mu = 1 \text{ TeV}$ ,  $X_t = 2.3 \text{ TeV}$ , all **Higgs limits** taken into account:

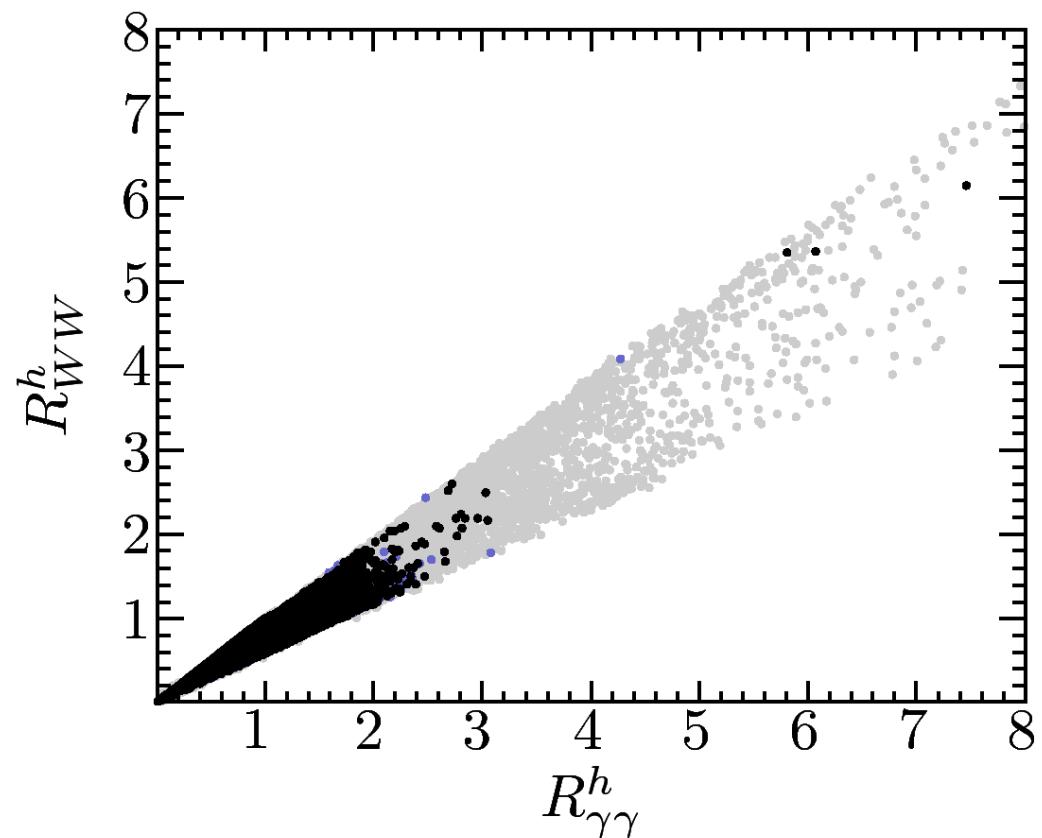
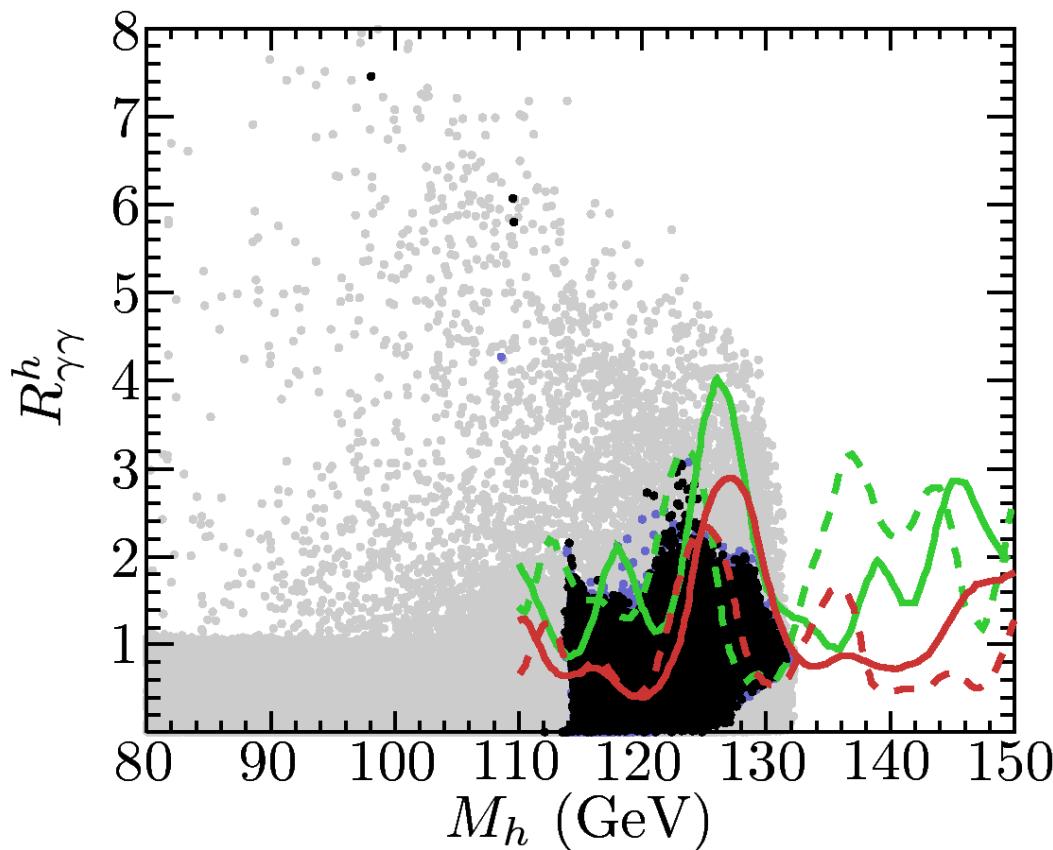


Possible:  $M_h = 98 \text{ GeV}$ ,  $M_H = 125 \text{ GeV}$ , ...

## Rate analysis in the MSSM:

[R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune '12]

Scan over the MSSM parameter space:



⇒ enhanced  $\gamma\gamma$  rate, suppressed  $WW$ ,  $b\bar{b}$  rate possible!

## 5. Conclusinos

- Finally we have the LHC running and searching for Higgs and SUSY
- Higgs searches: **we have a DISCOVERY !!! :-)**
  - ⇒ compatible with  $M_H \simeq 125.7$  GeV
- SM interpretation: fits well with predicted mass
  - fit to  $\mu$  or  $c_V, c_F$  ok
- MSSM interpretation: fits equally well – or even better?
  - light Higgs at 126 GeV
  - heavy Higgs at 126 GeV also possible

⇒ possible deviation from SM predictions could be explained
- Coupling determination:
  - theory assumptions on total width necessary!
  - ⇒ all fits so far compatible with SM

Back-up